Renewable and Sustainable Energy Reviews 37 (2014) 613–626

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Advances in wind energy resource exploitation in urban environment: A review

T.F. Ishugah [a], Y. Li [a,*], R.Z. Wang [a], J.K. Kiplagat [b]

[a] *Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China*
[b] *Energy Engineering Department, Kenyatta University, P.O. Box 43844-00100, GPO, Nairobi, Kenya*

A R T I C L E I N F O

Article history:
Received 20 October 2013
Received in revised form
30 April 2014
Accepted 17 May 2014
Available online 7 June 2014

Keywords:
Wind resource
Wind turbines
Street ventilation
Urban area

A B S T R A C T

Wind energy continues to stand out as a more established and mature technology to offset a large proportion of power. Efforts aimed at improving wind energy use to meet the energy demand in turbulent urban wind environment have been the main technical focus. In previous studies on wind resource and behavior in urban environment, different designs of horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) have been reviewed. This paper vividly captures the fact that wind resource has a great potential to be fully explored and developed in the urban environment. Varying ways of application and application techniques being applied for electrical generation, ventilation and pollution dispersion, onshore cooling and dehumidification of coastal urban cities, and economics and environmental benefits of applying wind energy in urban environments are summarized. Although many new ideas and solutions that factor technical, economical and environmental sustainability in urban areas are coming up every day, challenges in design are gradually being solved to take advantage of urban low and turbulent wind speed characteristics, installation space challenges, vibration and noise reduction, among others. Some of the unique solutions that have been and are being developed in the applications of wind energy technology in urban environments are also reported in this paper.

Contents

* Corresponding author. Tel./fax: +86 21 3420 6056.
E-mail address: liyo@sjtu.edu.cn (Y. Li).

http://dx.doi.org/10.1016/j.rser.2014.05.053
1364-0321/

1. Introduction

Increase in urbanization and industrialization around the world in recent years has led to a consequent rise in energy demand [1,2]. The expectation that more people will move to urban areas during the next few decades, especially in developing countries [3], has increased the need for more safe, secure, affordable and environmental friendly energy sources to satisfy the growing population [4–6]. In recent years it has been reported that approximately 75% of generated power is consumed in cities [7]. Generation of power within the city could be of great importance to help reduce both the generation load and transmission infrastructure. In addition, it may also minimize transmission losses due to reduced distance from users [8]. With the global energy demand in 2040 being expected to be about 30% higher than that of 2010 [9], it is predicted that more challenges such as increased environmental problems, depletion of fossil fuels and unstable oil prices will intensify. For these reasons, urgent need for the incorporation of alternative energy as well as energy efficiency measures has to be incorporated in urban planning and construction [10]. In recent years, it has been widely projected that wind energy will be among the best alternative energy sources needed for urban environment as it is clean, affordable, safe, and available in the long-term.

A lot of efforts have been made in the last few decades in exploring wind energy and improving wind energy application technologies to optimize performance and increase generation in turbulent urban wind profile [11]. Until now, two main approaches that have been integrated in large scale wind energy in urban settings are either locating wind energy farm in the periphery of the urban areas or integration of wind energy systems into the building design. Although the former has been widely employed in the recent years to overcome the challenges of turbulence, noise, size, space and visual impact created in the city among others, wind turbines outside the city comes with additional cost to provide electricity network to transmit power to a distant electrical load [12]. On the other hand, the latter eliminates the need to expand the high voltage electricity network to provide electricity for these loads although it faces challenges such as low or poor wind turbine output, shadow flicker, strong visual impact and to some extent vibrations and noise issues in buildings [13]. In addition it also requires detailed planning and design to be able to take maximum advantage of the wind in the urban environment.

As wind energy continues to stand out as a more established and mature technology to offset large proportion of power, it is important to note that more still needs to be done to exploit its full potential especially in urban environment. Many researchers are now studying urban wind characteristics [14], with many focusing on building mounted turbines [15,16]. Based on the World Wind Energy Report in 2011 [17], advances in wind turbines aerodynamics, their structural dynamics and micrometeorology have contributed to a 5% annual increase in the energy production of the turbines within the last 2–3 decades [18,19]. In addition to the improvement in energy output of the turbines, the weights of the turbines as well as the noise they emit have also been halved over the last few years [19–21]. Moreover, the designs have been improved to adapt to urban high rise applications [16]. As wind energy applications techniques continues to be applied in urban environment, researchers are also carrying out studies on pedestrian level wind in urban streets, thermal environments in urban areas, onshore flow in coastal urban areas, street ventilation and pollutant dispersion [22–24].

As wind energy resources, exploration and use in urban areas come under increasing scrutiny as part of renewable energy solutions, the need to consider the suitability of wind resources and its exploitation technology in the urban environment becomes a timely option. Kaldellis and Zafirakis [25,26] did a systematic study presenting the main trends, prospects and research and development directions in wind turbine technology. They investigated the main technological developments throughout the entire period of wind energy growth and outlined the most important research efforts associated with the establishment of wind energy. They further forecasted the most challenging future of research and development with a reflection on growth trend. Islam et al. [6,19] reviewed some progress and recent trends of modern wind energy technologies. Their research projection estimated that the Vertical Axis Wind Turbine (VAWT) can dominate the wind-energy technology due to their relatively less space requirements as well as potential to produce more energy compared to the Horizontal Axis Wind Turbine (HAWT). Dennis et al. [27] did an overview of world wind energy scenarios, the current status of wind turbine development, development trends of offshore wind farms, and the environmental and climatic impact of wind farms. Hameed et al. [18] did a comparative study of wind energy, problems, solutions and suggestion as a result of the implementation of wind turbine. They reported that wind energy development would reduce both environmental pollution and water consumption. However, noise pollution, visual interference and negative impacts on wildlife were still matters of concern.

To date, substantial publications on wind energy have mainly focused on regional wind energy assessment [28], wind speed distribution functions [29,30], economic aspects of wind energy [31] and regional wind energy policies [32]. Despite the fact that several works have been done on wind turbines aerodynamics and design [33], urban micrometeorology [34,35] and urban pollution dispersion [36,37], no or very little work has been done on wind energy resource and its applications in urban environment. This article, therefore, provides knowledge on wind energy layout in urban environment for natural ventilation, its potential in pollution dispersion as well as energy generation and its potential implications economics and environmental of urban environments. In addition, this paper also captures the fact that wind resource has a great potential to be fully explored and developed for onshore cooling and dehumidification of coastal urban cities. It is expected that this review will be useful for researchers as well as professionals, urban planners and architects, in the wind energy field.

2. Typical wind behavior in urban environment

Wind is the air motion relative to the earth that is created by difference in atmospheric pressure caused by difference in temperature due to difference in the intensity of solar radiation reaching the earth's surface [38]. Generally, wind moves in a

three-dimensional pattern from areas with high atmospheric pressure to those with low pressure. These atmospheric pressure difference as well as rotation of the earth creates currents within the atmosphere that work as an immense energy transfer medium. Besides these major forcing agents, other factors such as topographical features alter the wind energy distribution, especially on a local scale.

Very little research focusing on urban wind speeds with a view on wind turbine applications has so far been conducted [39]. Within an urban environment, the surface roughness that results to a high turbulence zone as shown in Fig. 1 greatly influences the wind speed and direction, hence its extractable power [40]. Since buildings are three-dimensional objects, the speed of wind flowing around them increases with height as the turbulence decreases [41]. At the same time, when air hits buildings and other obstacles in the urban environment, a resultant complex air whirls or waves are formed as shown in Fig. 2. Based on this turbulent effect, wind turbines needs to be placed high enough to capture strong winds and be above any turbulent air [42].

Since wind data analysis provides important information on siting, design and performance prediction of wind energy systems, several methods have been developed to derive wind speed data for specific sites based on measured data from other locations [45–47]. Widely used methods in estimation of wind resource includes; measurement [48], measure-correlate-predict [49], and, Wind atlas data [50]. Weibull and Rayleigh frequency distribution functions in particular have also been used for the estimation of wind resource [51–53]. Because of significant differences that might result due to differences in methodologies of data analysis, appropriate sampling frequency and averaging or correlation between actual measurement and prediction needs to be considered carefully [54,55].

In a broad spectrum, a combination of building shape, height and distance between buildings affects the direction and intensity of wind flow and can potentially affect its extraction for energy in urban environment [56,57]. Airflow through buildings has been researched by many researchers using different statistical analysis. Usually, the association between typical architectural forms and the wind environment in street canyons, semi-closures, courtyard forms and relatively open spaces in low-rise building complexes are investigated. The collected and recorded measured data captures information on wind speed and wind direction at different locations. Statistical analysis methods are then employed to identify key factors describing the effects of built form on the resulting airflows. Knowledge on how wind flows around buildings in urban environment is of great importance in making decision on the best location and design for wind turbine, ventilation, pollution dispersion and pedestrian comfort [58].

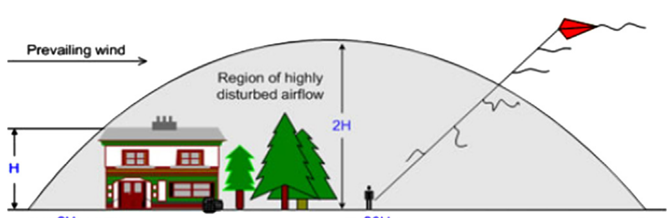

Fig. 1. Turbulence from obstacles results to a high turbulence region near obstacles [43].

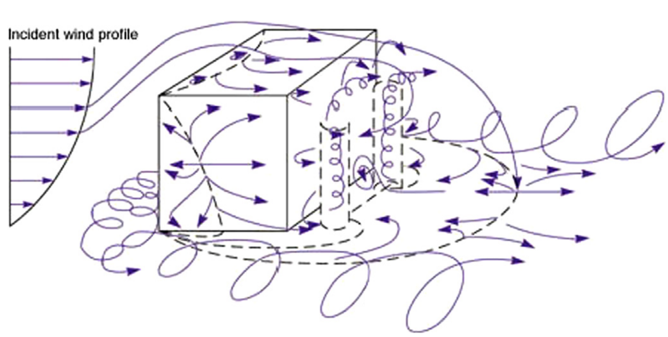

Fig. 2. Wind flow around buildings forms a complex air flow pattern whirls and waves [44].

2.1. Analysis of wind characteristic in urban environment

2.1.1. Urban morphology and surface roughness: case study in cities

Main wind characteristics such as surface drag, scales and intensity of turbulence, wind speed, and the wind profile in urban areas are greatly affected by roughness properties of the urban areas [59]. Critical and precise evaluation of such aerodynamic characteristics of wind in urban areas is therefore very significant in depicting and predicting urban wind behaviors [60,61]. Currently, three classes of methods can be used to estimate the surface roughness in urban areas. These methods include Davenport roughness classification [62], morphometric and micrometeorological methods [60]. The Davenport classification is a surface type classification based on the assorted surface roughness values that use high-quality observations. It covers a wide range of surface types. This method is not too helpful to be used to describe urban permeability in high density cities. Compared with the micrometeorological method, the morphometric method estimates the aerodynamic characteristics using empirical equations [63–65]. In the roughness layer, the flow region in the immediate vicinity of the urban canopy elements, wind flow behavior depends locally on the particular building arrangements resulting to a rather complex structure [66]. The roughness layer extends from the surface up to a level at which horizontal homogeneity of the flow is achieved. This occurs at 2–5 times the average canopy-element height [67], and in areas with high buildings, it can occupy a significant part of the urban boundary layer where most of the pollution problems occur.

As wind energy technologies mature, few studies that aim at wind turbine application in urban environment have been conducted. Wind energy assessment done in Masdar city with annual data collected under different heights at different temporal resolutions provides valuable feasibility analysis [68]. Fig. 3 shows the monthly average wind speed at the heights of 10 m, 30 m, 40 m and 50 m. According to the data collected, stronger and more stable average wind speeds were recorded as the height above the ground increased from 10 m to 50 m. The data showed that the windiest months were from May to August having an average wind velocity of about 4.5 m/s. Since annual average wind speed is close to the cut-in wind speed of most horizontal axis wind turbines (HAWTs), accurate wind energy production study for HAWT implementation at Masdar City had to be evaluated. Based

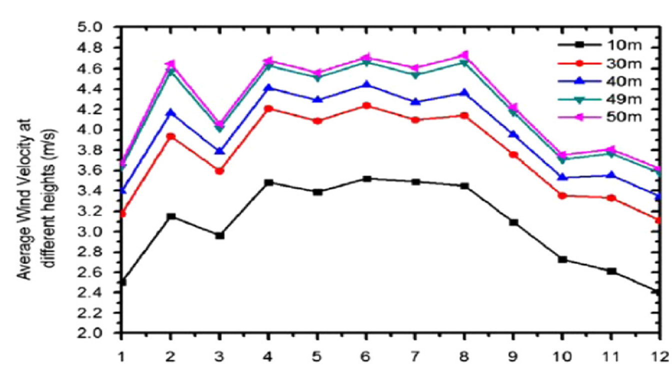

Fig. 3. Monthly average wind speed in 2010 (m/s) [68].

Table 1
Mean wind speed and turbulence intensity at different heights [101].

Height (m)	Yearly average wind speed (m/s)	Turbulence intensity (%)
10	3.06	19.82
30	3.74	15.01
40	3.95	14.03
49	4.20	1.97
50	4.25	12.71

on the values tabulated in Table 1, Masdar city was classified as a high-turbulent region at value of greater than 50% [69]. The annual collected data categorized Masdar city as poor wind region with high turbulence intensity, e.g., the turbulence intensity is as high as 19.82% at the height of 10 m [68]. However based on the investment-return and without accounting for the carbon trading, these results can support small wind turbine implementation.

2.1.2. *Wind flow characteristics in the urban canopy layer*

People living or working in urban centers will always notice windy spots. While many wind practitioners discount the appropriateness of placing wind turbines in urban areas, knowledge of wind flow characteristics in the urban canopy layer is relevant for a number of reasons: (a) it helps in the analysis of diffusion of pollutants in urban streets [70], (b) helps in evaluation of the wind comfort at pedestrian level [71], and (c) helps in characterization of the wind loading of small to medium size structures in the urban environment [40]. Until now, research into boundary layer climates in urban areas has predominantly been driven by an interest in pollution dispersal, and to a lesser extent pedestrian comfort. Research has shown that wind flow characteristics in urban environment are quite different from those of a Turbulent Boundary Layer, which are naturally developed over a homogeneous rough surface [72]. Kim and Baik [70] analyzed the effects of inflow turbulence intensity on flow and pollutant dispersion in an urban street canyon using a two-dimensional numerical model. They reported that the time series and residue ratio of pollutant concentration show that the inflow turbulence intensity significantly affects pollutant concentration in the street canyon. Furthermore they stated that as the inflow turbulence intensity increases, the pollutant concentration in the street canyon becomes low and hence more pollutants escape from the street canyon. Janssen et al. [71] did a case study on wind comfort situation of three main wind nuisance configurations in a complex urban area. Their comparative analysis showed that the choice of the comfort criterion can be influential on the decision of whether or not remedial measures should be considered, whether or not a building permit would be granted and whether or not the final design would provide a tolerable wind climate. This emphasized on the importance of standardizing the wind comfort assessment procedure, especially that concerning the comfort criterion.

In the urban canopy layer, the flow is almost completely governed by street or canyons' geometry (aspect ratio and length-to-depth ratios) and building height distribution especially in urban sections where buildings are closely spaced and a skimming flow pattern takes place [40,73], but less governed by the characteristics of the oncoming flow. In deep canyons as shown in Fig. 4, the vortices interact poorly with the external wind flow above the canyon resulting in very little or completely insignificant contribution to the removal of exhaust gases [74]. Relatively short canyons provide better ventilation around corners [75]. This effect is especially facilitated with the formation of corner vortices. This effect however fades with increasing street length. The presence of

Fig. 4. Deep urban canyon [78].

intermittent vortices at the building corners creates a 'convergence zone' in the mid-block region of the street canyons or intersections resulting in highest degree trapping of pollutants [76]. Within urban street intersections, wind vortices, low-pressure zones and channeling effects may cause maximum trapping of pollutants in the lower portion. In cases of high-rise buildings, forming intersections provides better ventilation around corners due to the formation of corner vortices [77].

2.1.3. *Wind flow characteristics along rivers, seaside and open areas*

In addition to the above mentioned processes affecting the urban air quality the airflow over larger-scale urban features, such as rivers or parks and on the seaside also need to be understood [79]. The quality of air in urban environment generally depends on the ventilation processes [80]. In addition, the atmospheric boundary layer depth also determines air pollutant concentrations [81]. It is therefore important to have knowledge of all the processes affecting the urban air quality. A lot of studies have been done on wind flow on buildings as mentioned above. However, there are some city forms (for example presence of rivers, parks, and open grounds) that have proved challenging to study using localized point measurements methods due to their formation and siting nature [80]. Despite this, the use of ground-based remote sensing has proved helpful in providing a more representative analysis of airflow in such urban locations.

Previous research has shown that rivers have the potential to provide a key mechanism for ventilation in cities [82]. Their presence provides similar mechanism to those provided by urban street canyons for the airflow varies in space and time in the vicinity of rivers. Wood et al. [80] revealed that the turbulence level of airflow across the river and its surrounding environment varies according to the roughness within the river environment.

This significantly affects the air quality and pollution dispersion around urban rivers, especially given that many cities have high traffic rates on roads located on riverbanks.

Until now, latent and sensible heat fluxes above rivers [83] have received comparatively little attention. In addition, some mesoscale processes can also affect ventilation to a significant extent. Within the urban environment, wind speed is generally greatest when the wind flows parallel to the river. However, lower relative wind speeds can be found when the approach airflow is perpendicular to the river due to change in aerodynamic drag. The air flowing over the river generally becomes less turbulent after passing through the building [80]. In general, the complexity of the airflow changes according to space and time due to the changes experienced in ground height as well as in building heights.

3. Common types of wind turbines currently being used in urban environment

The kinetic energy in the wind is harnessed by wind turbines and transforms it into electrical power or mechanical work [84]. Since wind profiles in urban areas tend to be more turbulent due to the presence of buildings, trees along the streets, and other obstacles [85], urban environment has unique challenges in development of wind energy systems. Much of the on-going developments on these systems are noise reduction, esthetics, integration into architectural systems, and efficient use of the available wind resource [86]. Over the past few years the major advancements in development trend has been to increase the size, efficiency and reliability of wind turbines, making their deployment more cost-effective. Although there are many different configurations of wind turbines [87], two classified types of wind turbines used in urban areas are horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) [88].

3.1. Horizontal axis wind turbines (HAWTs)

Until now, the common types of wind turbines used in urban environment are horizontal axis wind turbine types. Modern utility-scale of HAWTs is near the theoretical maximum for efficiency, a reason why the industry focuses on that type of turbine [89]. These types of wind turbines have their axis of rotation of the blades in a horizontal position [90]. During operation, the wind blows through blades, converting wind's energy into rotational shaft energy. The propeller-type rotor mounted on a horizontal axis needs to be positioned into the wind direction by means of a tail or active yawing by a yaw motor [91,92]. Due to the sensitivity of HAWTs, changes in wind direction and turbulence especially in urban environment negatively affects the performance because of the required repositioning of the turbine into the wind flow [93,94]. The real and perceived problems with large HAWTs in urban environment are the dangers to birds and aircraft, esthetics, manufacturing issues, maintenance, etc., HAWT's blade sizes are also part of their limitations in their use in urban environment [95]. After certain length of the blade, you cannot make them larger. However, stacking up large VAWTs, possibilities of building a larger structure within the urban exists, opening up more change for VAWTs penetration in urban market. Fig. 5 shows different orientations of HAWTs that can be used in urban environment. Their main design features and design objectives are summarized in Table 2.

3.2. Vertical axis wind turbines (VAWTs)

The vertical axis wind turbines have a vertical axis of rotation of blades about the vertically positioned shaft [104]. The advantage of these types of machines is that they do not have to face in any particular direction with respect to wind; this makes them perfectly suitable for urban environment [38,95,103]. Another benefit of these types of turbines is that the generator and gearbox can be installed at ground level making them easy to service and repair apart from being suitable in building mounting in urban environment. Due to the turbulence nature of the wind in the urban environment, the vertical wind turbines provide a much better option for small scale production as they can handle much higher turbulence and varied wind speeds as compared to HAWTs. Consequently, because of their lower elevation, they are ideal for cities and other densely populated areas where it has not been possible to set up wind turbines [13]. In general, most of the

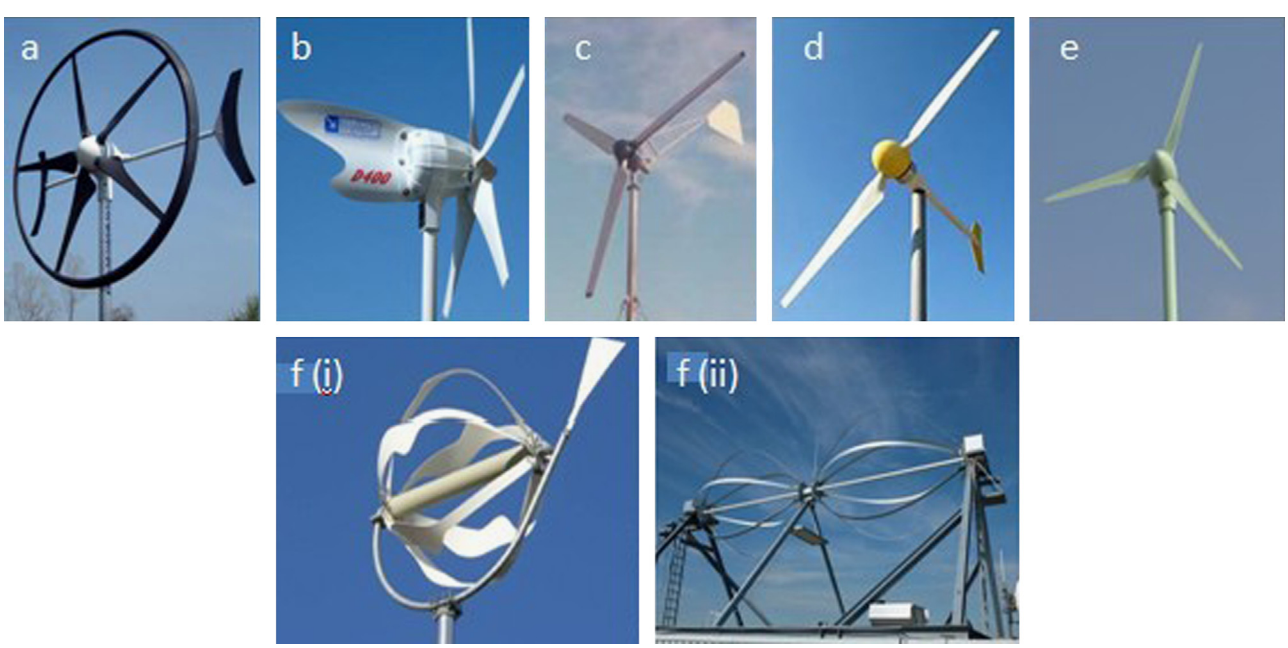

Fig. 5. Examples of HAWTs. (a) Swift wind turbine [96], (b) Eclectic wind turbines [92], (c) Fortis Montana wind turbine [97], (d) Scirocco wind turbines [98], (e) Tulipo wind turbine [99], and (f) the Savonius type, (i) Energy Ball [100] and (ii) WindWall [101].

Table 2
Orientations of horizontal axis wind turbines [102,103].

HAWT type	Design features	Main purpose
Swift wind turbine	They are small wind turbines with thin blades encircled by a ring to reduce vibration and diffuse noise to a level of less than 35 dB	Designed to reduce noise, making them more suitable to be installed on roof tops especially in urban areas
Eclectic wind turbines	Their rotor blades designs are optimized for low wind speed, i.e., at 11 m/s, this type of turbine can still provide sufficient power	They are small and light enough making them suitable to be easily attached to most building in urban areas
Fortis Montana	Blades are designed to be really quiet (makes 1-3decibels above the background noise) with a low tip speed – you really can't hear this turbine from 50 m	They are small wind turbine used mostly for home electrification by individual users to save on their electricity
Scirocco wind turbines	Designed to incorporate features found on much larger turbines, such as variable pitch blades and an optimized two blades rotor	Optimize lower wind speeds with an excellent cost/performance ratio
Tulipo wind turbine	It is specially equipped with fixed stall blades that require minimum maintenance. They have specially designed blades which rotate at relatively low speed emitting almost no noise or vibrations	Can generate high electrical power at low nominal wind speed
Savonius type	These types of HAWTs use drag forces to create rotation of the shaft Energy Ball shown in Fig. 9 (a) has a tail but with an innovative rotor construction, six half-circular blades forming a spherical construction WindWall shown in Fig. 9 (b) has the axis fixed to the roof in a way that it can extract the wind from only one direction making it suitable only for locations where the wind from one direction strongly prevails	They are meant to be self-starting when designed with at least three scoops whereas those designed with long helical scoops give a smooth torque

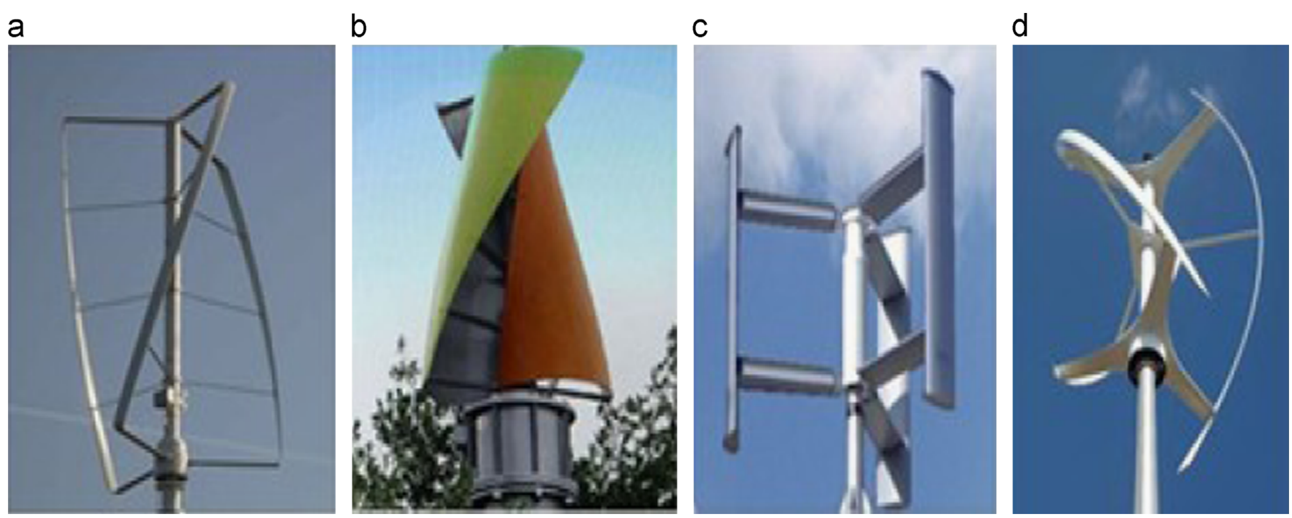

Fig. 6. Different types of Darrieus wind turbines. (a) Turby turbine [111], (b) WindSide [112] Turbine, (c) Ropatec turbine [113], and (d) Gorlov helical turbine [114].

electricity produced by VAWTs is utilized on-site. These types of wind turbines are preferred in small scale installations, and generally generate very little energy as compared to their horizontal axis counterparts [105].

The overall increase in the use of smaller VAWTs in the urban environment has been due to the ease and low manufacturing cost for smaller turbines. These turbines are more scalable and can be installed at a lower elevation above the ground. For these reasons, the market share of these types of turbines is improving due to their relatively low maintenance costs as well as decreased impact they cause on birds and aircrafts. Compared to farms of HAWTs, the VAWT farm has three times the power density at one tenth of the height [106]. There are four main types of vertical axis wind turbines used in urban environment today as shown in Fig. 6 and summarized in Table 3. They are namely; Darrieus, Gorlov, Giro Mill and Savonius.

As mentioned before, unlike the large open windmill farms, extracting wind energy in an urban scenario is challenging because of the tight space constraints and the fact that wind profile is highly turbulent with rapid fluctuations, both in terms of magnitude as well as direction. Due to this, development of a revolutionary and extremely efficient small-scale variable pitch VAWT, with a simplified blade pitching mechanism, is among the recent main research topics. Kinematic coupling of the blade pitching mechanism with turbine rotation could reduce the additional power required to pitch the blade. In addition, it enables easy blade pitching with changes in wind direction [107]. This capability of the present VAWT pitch mechanism, to immediately respond to changes in wind direction, is the key to maximize the power extraction in urban environments where wind direction changes rapidly [108]. Recent research on the VAWT blades is also focusing on light-weight systems to minimize turbine structural loads and provide high strength-to-weight ratio [109]. This reduces the cases of large bending and torsional deformations due to the large transverse centrifugal loading, which would hamper the turbine efficiency during operation. The present blades use an innovative, high strength-to-weight ratio, composite blade structural design, which is similar to the blades used in case of the flying cyclocopter [110], where the blades operate under larger dynamic loads due to the higher rotational speed of the powered rotor.

With the idea of designing and building suitable small-scale wind turbines for urban environments in mind, various HAWTs and VAWTs have been researched on to determine their suitability. Simple construction and cost of materials has been a major driving

Table 3
Orientations of vertical axis wind turbines [93,103].

VAWT type	Design features	Main purpose
Darrieus wind turbine	Uses three or more blades to reduce torque ripple which results in a higher solidity for the rotor. Different orientations of Darrieus wind turbines are Turby turbines, WindSide Turbines, and Ropatec turbine.	Designed for high rooftops use i. It is capable of generating enough electricity at very low wind speeds and in extreme temperatures, hence reduces the electric bill for a typical home.
Gorlov helical turbine	It is a subtype of Darrieus turbine designed in a helical configuration.	Designed to provide self-starting with lower torque ripple as well as low vibration and noise, and low cyclic stress.
Giromill	It is a subtype of Darrieus turbine with straight blades	Designed to give variable pitch, which makes it have a high starting torque with a lower blade speed ratio and provides more efficient operation in turbulent wind, to reduce the torque pulsation and make it self-starting.

factor in the decision making process. Large utility-scale HAWTs are very expensive to produce and also require enormous manufacturing facilities. Smaller VAWTs can be produced in more modest facilities using standard techniques leading to lower overall costs. Despite the fact that they have not been commercially successful, VAWTs have been preferred for small scale power production in urban environment as they possess the required design factors [115]. Until now, HAWTs are highly developed and currently available in the entire existing wind farms [19]. Studies estimate that within the next 2–3 decades, VAWTs can dominate the wind-energy technology, especially in urban environment, because they require less land space and using the same space; they are capable of producing more energy than that of its counterpart [116].

Fig. 7. Stand-alone wind turbine at Great Lakes Science Center, Cleveland [124].

4. Wind resource harnessing and application techniques in urban environment

4.1. *Wind power extraction for electricity generation*

Wind energy systems can be economically feasible in the urban environment as they eliminate the need to expand the high voltage electrical supply. This is because wind energy systems place the energy source close to the electrical load. To a greater extent, intensive research and development in renewable energy in urban environment has given much attention on the use of wind energy for electricity generation [117]. Unique solutions for the application of wind energy technology in urban environments have been and are being developed. Until now, there are several ways in which wind energy generation systems for electricity production have been integrated into urban environments [21] for electricity generation. Among them includes, systems such as stand-alone wind turbines in urban locations, retrofitting wind turbines onto existing buildings and full integration of wind turbines together with architectural structure.

4.1.1. *Stand-alone wind turbines*

Stand-alone wind energy systems are best suited where the grid power is unavailable [118], and the power generated is fed into batteries for storage instead of into the mains grid. For this reason, stand-alone systems produce power that is independent of the utility grid [119]. Due to the turbulent nature of wind in urban environment, the power output stability significantly depends on the type of the wind turbine installed as well as the location within the turbulence region [120]. Lower power range wind turbines, particularly the permanent magnet synchronous generator (PMSG), have been chosen for urban environment due to their low cost, reduced power losses and simple construction [121].

Although wind speeds are generally lower in built-up areas, large-scale urban wind energy can be successfully implemented as shown in Fig. 7. These can be found in many urban areas especially in elevated locations or coastal locations within the environs of urban environment. In general, moving large-scale, stand-alone wind turbines into the built environment have several advantages; among them are minimized transmission losses and cost. Despite the fact that large-scale grid-connected wind turbines have proved to be economically viable in many parts of the world, design of small-scale stand-alone wind power sources for urban locations has indicated a high potential of reaching a commercially feasible state [122]. With the large foreseen potential market for wind turbines that can operate either as stand-alone generating units, more technical solutions are being proposed every day to include the aspects of difficult operating conditions within the urban environment [123], challenges of low capacity factor, high battery costs, and finite capacity to store electricity that leads to wastage of the extra energy generated are being addressed [122].

4.1.2. *Retrofitting wind turbines onto existing buildings*

One of the techniques being considered in urban environment is the use of micro-wind turbines designed to be mounted on new and existing homes [16,103], for small-scale electricity generation. Small-scale turbines are proving viable as building retrofit solution especially with micro-wind turbines of various types, mentioned in section three above, being commercially available [5]. Although many governments are providing attractive schemes to encourage the application of micro-wind turbines in urban area areas [103], such small-scale wind turbines for building integration may not always be esthetically pleasing. In addition, they are also hazardous due to high frequent failures of the turbine blades, which have raised public concern over issues of safety, noise, vibration and visual impact [125]. A few researchers however have come up with new innovative devices such as the power augmentation-

guide-vane (PAGV) [126] and the Omni-direction-guide-vane (ODGV) [127] for integration with wind turbines to solve or minimize the challenges of safety, noise, vibration and visual impact. The ODGV is a novel revolution of PAGV that surrounds a vertical axis wind turbine (VAWT), to improve the self-starting behavior and the wind turbine performance. This is achieved by increasing the rotor rotational speed for on-site generation.

It has also been noted that retrofitting wind turbine into existing building causes an obvious difference in visual impact between the conventional wind turbine and the one that is specially designed for urban areas [128]. The overall performance of the retrofitted wind turbine varies depending on the roof position, roughness of the upwind area, size of the building, upward edge rounding and the yaw of the free stream wind [86,129]. One iconic retrofit project is the Boston Logan airport building [130], as shown in Fig. 8. A fleet of miniature wind turbines at Boston Logan International Airport has been considered to give the best view of the city. The 20 turbines installed are uniquely created for urban environment [131], where wind turbines are specifically engineered to take advantage of the acceleration effect of wind as it passes over the building parapet. Each one kilowatt six-foot-tall turbine is affixed at a unique angle to capture the winds that gust through Boston Harbor and climb the building's walls [130]. The installation was estimated to generate about 100,000 kW h annually, which is equivalent to 3% of the building's energy needs [132].

4.1.3. Full integration of wind turbines together with architectural form

This method involves a relatively advanced technical and construction plan that generally leads to a huge capital investment during development. Building integrated wind turbines are gaining more attention for urban on-site clean energy generation. Options for integrating wind turbines into the building under this project are usually developed during the initial phase of the project. Although this technique might seem fascinating from the architectural and aerodynamics point of view, large-scale buildings integrated with wind turbine technology are rare in major cities due to their challenging issues of safety, noise, vibration and visual impact [134]. However, noise and vibration produced by HAWTs can be mitigated by use of VAWT, which comparatively reduces the level of noise and vibrations. Integration of the power augmentation guide vane (PAGV) and the Omni-direction-guide-vane (ODGV) in design of VAWT has also enhanced reduction in noise as well as increased wind speed that enters the turbine [127,135].

One of the projects that features roof mounted wind turbines integrated building structure is the COR project by the

Fig. 8. Boston Logan airport building wind power turbines [133].

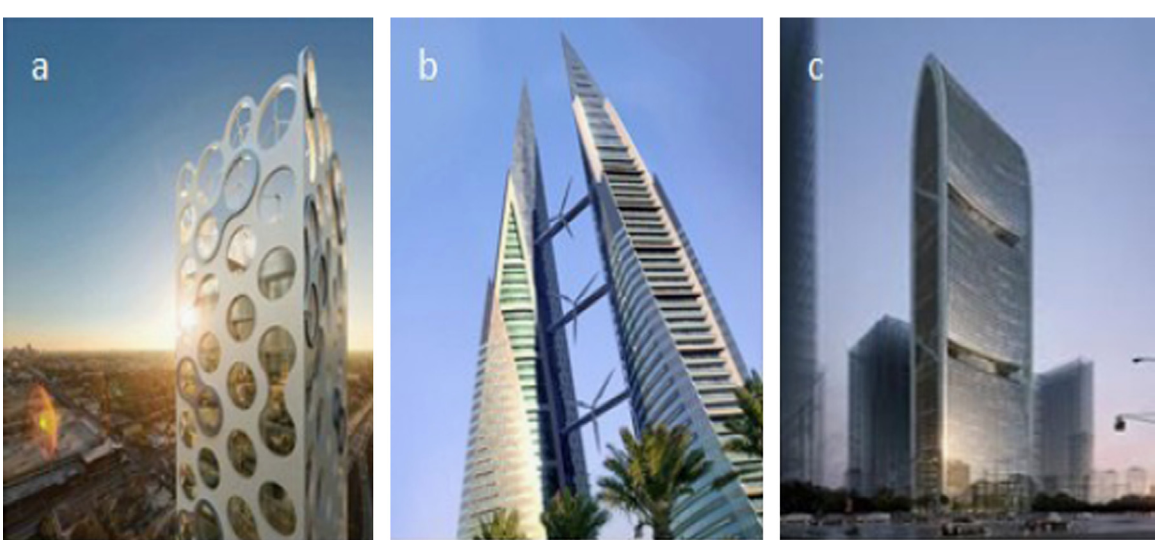

Fig. 9. (a) COR project external view [143], (b) Bahrain WTC twin towers [139], and (c) SOM's Pearl River Tower [144].

OPPENHEIM architecture and design [136], shown in Fig. 9a. The project comprises of several horizontal axis wind turbines located at different heights all over the four facades. The project helps overcome the short fall of horizontal axis wind turbine not being able to harness wind from changing directions [137]. Probably among the most popular of the recent examples of building integrated designs using the funneling concept are the Bahrain WTC Twin Towers [138,139] shown in the Fig. 9b. Bahrain's iconic landmark is the first in the world to be integrated on such a scale into a commercial development using three 29 m-diameter turbine blades horizontal axis wind turbines for energy generation [140]. The energy that can be generated from the turbines, when fully operational, amounts to between 1100 and 1300 MW h per year. This accounts to approximately 11–15% of the office tower's electrical energy consumption. Another attractive concept of building integration with wind turbine and aerodynamic geometry is SOM's Pearl River Tower [140], shown in Fig. 9c. The tower's curvilinear form funnels air through two inlets in the facade where two vertical axis wind turbines (5 m high Windside wind turbines), shown in Fig. 6b. are sited to take advantage of the prevailing winds producing about 5% of the building's total energy needs [141]. The distinct feature of this building is that it is not dependent on having two Towers building to funnel wind and the wind turbines are visually intrusive [142].

Despite increased interest in building integrated wind turbines, several challenges have been reported in their implementation. One of the major limitations is that turbulence and wind shear that is characteristic of urban environments has resulted to low and unexpected performance [145]. Considering the location of the buildings, additional safety measures must be considered. For example, selection of wind turbines with low/minimum noise for urban environment to comply with the low noise levels, avoiding locating the turbines in the sensitive areas should be avoided. In addition, providing special mounting for the turbines to absorb or isolate vibration is also important [146]. With special considerations given to these challenges, building integrated wind energy systems can offer a secure, equitable, affordable and sustainable energy supply, which is vital for future prosperity.

4.1.4. The highway turbine

This is a novel way of re-capturing some of the energy expended by vehicles moving at high speeds on urban highways, as shown in Fig. 10. This kind of turbines installation is being proposed by an Arizona State University [147]. The concept is built based on the effects of air turbulence generated by vehicles moving at a high speed, particularly heavy trucks. It is understood that in many built up areas there is enough constant traffic volume that can maintain a steady airflow through much of the day. Electricity extraction involves mounting horizontal axis wind turbines above the roadway, which are then driven by the moving air generated by the passing traffic. The electricity generated by spinning these turbines can be used locally or be fed into the grid. The main challenge is the nature of the turbulent airflow generated by moving traffic and the safety of the installation to the traffic.

Fig. 10. Horizontal axis wind turbines installed in Urban Highway [147].

4.1.5. Onshore and offshore wind power generation

The coastal regions are usually the most economically developed with high electricity demand, thus the exploitation of onshore and offshore wind energy does not only help ease pressure on power supply in those areas but also helps reduce greenhouse gas emissions [148]. Development of onshore wind farm for power generation on the seaside of coastal cities has majorly been restricted by land availability [28,149]. Other problems such as wind turbine noise and their visual impact on the natural environment are among the main reasons for people to refuse to accept development of onshore wind turbines close to residential areas [150,151]. In efforts to solve the challenges involved in onshore turbine development, offshore wind technology has been employed in some cities around the world [151,152].

Although offshore wind turbines operate in the same manner as onshore wind turbines, installation at the sea offers numerous advantages over the onshore installation. First, there is a lot more available space and fewer complaints about noise and visual intrusion. Second, wind over the water is generally stronger, more consistent and much smoother than wind over the land, resulting in significantly higher production per unit installed. Third, wind turbines can be bigger than those on land because it is easier to transport very large turbine components by sea. In addition, offshore wind farms can be installed close to major urban centers, requiring shorter transmission lines to bring this clean energy to these high energy cost markets. For these reasons, offshore wind power generation becomes one of today's fastest growing energy technologies and is going to be the future focus of development in many countries around the world [153,154]. At the end of 2011, there were 53 European offshore wind farms in waters off Belgium, Denmark, Finland, Germany, Ireland, The Netherlands, Norway, Sweden and the United Kingdom, with an operating capacity of 3813 MW [155], while 5603 MW was under construction [156]. More than 100 GW (or 100,000 MW) of offshore projects are proposed or under development in Europe [157]. However, compared to onshore wind farms, offshore wind turbines are more expensive and difficult to install and maintain due to the variable and rough sea conditions.

At present, the major barrier to the deployment of offshore wind energy on a massive scale is the high costs of offshore wind facilities. Nevertheless, significant cost reduction in the offshore wind sector could be achieved by using future advanced technology to optimize every stage of development, manufacture, installation and operation [158].

4.2. Wind driven roof ventilators

Ventilation is changing of air in an enclosed space. Lack of ventilation can cause excessive humidity, condensation, overheating and a build-up of odors, smokes and pollutants [159,160]. Ventilation, therefore, plays an important part of HVAC (heating, ventilation and air-conditioning) systems, which are very energy intensive. Roof ventilators can be recognized as a VAWT type because they spin vertically and have the same shaft position, blade and operate in the

same manner as VAWTs. The main function of the free spinning roof ventilator is to provide fresh air in roof space and living area all the year round with an additional function to generate electrical energy to subsidize on grid power expenses. Natural ventilation can passively or actively be enhanced by wind driven ventilation techniques.

Passive wind driven ventilation techniques involves strategic placement of openings, like windows and doors [161], in buildings to cut down on artificial cooling; incorporation of artria and courtyards [162] which provide a relatively enclosed space to channel and direct airflow into some openings and results in convective natural ventilation within and around the building; and incorporation of wind towers and wind catchers enables capture of the wind at roof level and redirects it down into the building. Active wind driven ventilation techniques involve systems such as turbine ventilators usually installed on top of the roof where higher wind speeds are available for most buildings and rotates in its vertical axis to create an updraft of air inside the turbine as well as hybrid ventilators which combine the traditional turbine ventilator with a small DC fan powered by solar cells [163] enhancing the ventilation rate at low wind speeds [164]. Study done by Shun and Ahmed [165] demonstrated that a single hybrid ventilation device had a much improved operational flexibility and performance characteristics when compared with existing ventilation technology. In addition, air extraction was possible even under conditions of zero wind and bad light. Their study represented a significant step forward in promoting the use of clean energy for the purposes of building ventilation, especially in urban environment.

4.3. Onshore cooling and dehumidification of coastal cities

Wind regimes in the coastal urban areas are one of the most pronounced micro and meso-climate factors. Although the basic features of the local climates that accompany these wind regimes have been studied for some time, more research is still needed to refine understanding of their internal dynamics in urban areas.

Daytime onshore flow from a cool water surface to warmer coastal urban lands is one of the most important common wind regimes. Lake- and sea-breezes are common varieties of onshore flow. Onshore flow into adjacent urban environment involves not only wind but also carries lower air temperature and different humidity on to the land. This produces a zone along the shoreline in which climate differs from that found in the inland built up environment. Contrasts in atmospheric conditions are frequently great enough to have several practical effects on human thermal comfort and building heat loads. These effects are easily perceived and recognized by residents of coastal cities. People definitely feel cooler with the onshore flow [24]. Building temperatures and cooling requirements are lower. This is as a result of lower air temperature and higher wind speed accompanying the onshore flow.

4.4. Street ventilation and pollutant dispersion

The urban thermal environment has been worsened by the Urban Heat Island (UHI) effects [166,167], now regarded as one of the most serious urban environmental problems in the world. Increasing urbanization and concern about sustainability and quality of life issues have produced considerable interest in flow and dispersion in urban areas. Wind conditions in urban areas play a very important role in removing or dispersing the airborne pollutants as well as mitigating the UHI effects in urban canopies or providing cleaner external (rural or onshore) air [168]. Urban environment with high-rise buildings and narrow streets act as blockages and pathways to the approaching wind. Consequently, they affect the urban wind ventilating capacity.

In urban areas ventilation capacity is dependent mainly on the magnitude of the street volume, the total city length, the flow rates through street openings and street roofs due to mean flows and turbulent fluctuations. For these reasons, a good choice is to build taller buildings and wider streets to capture more air into the street network for city ventilation, at the same time, it utilizes some large open space like gardens, football fields, parks, river etc., to separate a continuously city scale (up to 10 km) built-up urban area into several neighborhood scale urban areas.

Terrain undulations are likewise a significant factor in the dynamics of the urban boundary layer and urban dispersion, even for moderate terrain slope ratio (0.26) and small hill to building height ratio [169]. Atmospheric boundary layer dispersion properties are affected non-linearly with small hills slightly reducing velocity variances while large hills strongly increasing the same. Large population centers are frequently located in coastal urban areas (e.g., San Francisco, Barcelona, Tokyo, and Brisbane). In addition, most of the coastal cities have hilly terrain with typical height variations on the order of or larger than the building height is common.

5. Economics and environmental benefit of application wind energy system in urban environment

Wind energy exploration and exploitation is increasingly becoming an important economic booster in reducing the exposure of our economies to fuel price volatility. This is especially the case for economies that depend on imported fuel from politically unstable countries [170]. Use of wind turbines in urban environment provides economic balance because power generation costs cannot be influenced by fluctuating fuel costs. Like any other energy system, the basic costs of wind energy is determined by various factors such as; upfront investment costs, wind turbine installation costs, capital cost, operation and maintenance costs, other project development and planning costs, turbine lifetime and electricity production cost [5].

Approximately 75% of the total cost of energy for a wind turbine is related to upfront costs such as the cost of the turbine, foundation, electrical equipment, grid-connection and so on [171]. Wind turbines service and maintenance constitute a sizeable share of the total annual costs of a wind turbine. However, compared to most other power generating costs, they are very low.

Micro-generation technologies, especially those with appreciable resource, have the potential to reduce built environment related CO_2 emissions coupled with reductions in consumers' electricity costs. In many cases payback on capital investment is within the lifetime of the device. The cost per energy produced and payback period of wind energy systems in urban environment are greatly dependent on variable parameters from city to city and time to time making it difficult to come up with specific information for each turbine [172,173]. Wind speed in urban sites has the greatest influence on wind system economic viability. It therefore poses a very important factor when siting a wind turbine. Till present time, there are very few wind energy system installations in urban environment to be able to draw definitive conclusions about their success of installation [174]. In general tall buildings and tower blocks seem to offer best conditions to capture higher wind speeds, due to less wind flow influence, and as a result making wind energy turbine installation in cities viable.

6. Social acceptance of wind energy exploitation in urban environment

Exploitation of wind energy in urban environment has generally been considered as an important contributor to renewable energy, climate, and energy security by many countries around the

world. Increase in the number of wind energy systems and other exploitation strategies suggest a general acceptance of wind power [175]. However, social acceptance involves a wide range of stakeholders, including the general public, various institutions and associations, project developers, financiers, and residents of local project host communities [176]. It also touches many disciplines, including medicine and psychology (aspects of well-being), biology (ecosystem effects), psychology and sociology (procedural fairness), policy and spatial planning, and economics (distribution of costs and benefits). In specific, social acceptance defines the societal consensus and provides a powerful indicator towards wind energy. This review article, however, offers limited analysis on social acceptance of wind energy exploitation in urban environment although it must be noted that the issue of social acceptance must be taken into account in existing and new wind power initiatives and projects. In assessing the social acceptance, key aspects such as policy and strategy, well-being and quality of life, cost and benefit, consultation and public involvement, and implementation strategies needs to be considered.

7. Conclusions

As it is expected that more people will move to urban areas during the next few decades, more energy sources that are safe, secure, affordable and environmental friendly need to be exploited to be sufficient for the growing population. Wind energy resources, their exploration and use in urban areas are coming under increasing scrutiny as part of renewable energy solutions. Due to these factors, more unique solutions for the application of wind energy technology in urban environments have been and are being developed. New wind energy systems development in urban areas allows designers to architecturally integrate the wind energy system into the building and other urban structures. In using new wind energy technologies incorporated in urban environment, some of the challenges such as low or poor wind turbine output, shadow flicker, strong visual impact and to some extent vibrations and noise issues in building and other structures are able to be mitigated.

Wind technologies in urban environment is a quite new field in development with great potential where many new ideas and solutions are being developed every day for economical and sustainable exploitation through well planning and design of systems. Until now, the common types of wind turbines used in urban environment are horizontal axis wind turbine types. Although simplicity in construction and low cost of materials has been a major driving factor in the decision making process, VAWTs have been preferred for small scale power production in urban environment as they possess the required design factors to take advantage of urban low and turbulent wind speed characteristics, installation space challenges, vibration and noise reduction, among others.

One of the main economic advantages that wind energy system will provide when incorporated within the urban environment is the placement of the energy source close to the electrical load. This eliminates the need to expand the high voltage electricity network to provide electricity for these loads. Other than generating electricity in urban areas, urban wind turbines help to maintain a more natural environment in our cities through zero greenhouse gas emission. Moreover as our energy future is certain to rely increasingly on a multiple renewable sources, wind energy has a place in the built environment for some time to come.

With all human methods, not all agree with wind power harvesting for urban applications. However, recent work done indicates that urban wind power is a resource that is too good to go to waste given the energy and environmental challenges we are facing. Thoughtful planning, site examination and turbine selection can help us master the unruly urban wind for good use.

Acknowledgment

This work is supported by the Key project of the Natural Science Foundation of China for international academic exchanges under the Contract no. 51020105010. The support from the Ministry of Education Innovation Team (IRT 1159) is also appreciated. The first author sincerely thanks the Chinese government for the scholarship which enabled him to carry out the research smoothly. In addition, appreciation also goes to Kirumba George Chira for the input offered in manuscript refinement.

References

[1] York R, Rosa EA, Dietz T. STIRPAT, IPAT and ImPACT: analytic tools for unpacking the driving forces of environmental impacts. Ecol Econ 2003;46:351–65.
[2] Jones DW. How urbanization affects energy-use in developing countries. Energy Policy 1991;19:621–30.
[3] Al-mulali U, Fereidouni HG, Lee JY, Sab CNBC. Exploring the relationship between urbanization, energy consumption, and CO⟨sub⟩2⟨/sub⟩ emission in MENA countries. Renew Sustain Energy Rev 2013;23:107–12.
[4] Perez-Lombard L, Ortiz J, Pout C. A review on buildings energy consumption information. Energy Build 2008;40:394–8.
[5] Bahaj A, Myers L, James P. Urban energy generation: influence of micro-wind turbine output on electricity consumption in buildings. Energy Build 2007;39:154–65.
[6] Saidur R, Rahim N, Islam M, Solangi K. Environmental impact of wind energy. Renew Sustain Energy Rev 2011;15:2423–30.
[7] Dodman D. Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories Environ Urban 2009;21:185–201.
[8] El-Khattam W, Salama M. Distributed generation technologies, definitions and benefits. Electr Power Syst Res 2004;71:119–28.
[9] Dashwood J. The outlook for energy: a view to 2040. Aust Energy Options: Renew Effic 2012:45.
[10] O'Brien G. Vulnerability and resilience in the European energy system. Energy Environ 2009;20:399–410.
[11] Tripanagnostopoulos Y, Tselepis S, Souliotis M, Tonui J, Christodoulou A. Practical aspects for small wind turbine applications. In: Proceedings of EWEC; 2004.
[12] Zeng H. Integration of renewable energy with urban design: based on the examples of the solar photovoltaics and micro wind turbines. Massachusetts Institute of Technology; 2011 available at http://dspace.mit.edu/handle/1721.1/69461.
[13] Müller G, Jentsch MF, Stoddart E. Vertical axis resistance type wind turbines for use in buildings. Renew Energy 2009;34:1407–12.
[14] Research U. Wind energy. Available from: ⟨http://www.eeca.govt.nz/eeca-library/renewable-energy/wind/report/umr-omnibus-results-windresearch-report-04.pdf⟩ [accessed 23.08.08].
[15] Mertens S. The energy yield of roof mounted wind turbines. Wind Eng 2003;27:507–18.
[16] Grant A, Johnstone C, Kelly N. Urban wind energy conversion: the potential of ducted turbines. Renew Energy 2008;33:1157–63.
[17] WWEA. The world wind energy report 2010. Available from: ⟨http://www.wwindea.org/home/images/stories/pdfs/worldwindenergyreport2010_s.pdf⟩ [retrieved 29.03.12].
[18] Hameed Z, Hong Y, Cho Y, Ahn S, Song C. Condition monitoring and fault detection of wind turbines and related algorithms: a review. Renew Sustain Energy Rev 2009;13:1–39.
[19] Islam M, Mekhilef S, Saidur R. Progress and recent trends of wind energy technology. Renew Sustain Energy Rev 2013;21:456–68.
[20] Henriques J, Marques da Silva F, Estanqueiro A, Gato L. Design of a new urban wind turbine airfoil using a pressure-load inverse method. Renew Energy 2009;34:2728–34.
[21] Chong W, Fazlizan A, Poh S, Pan K, Ping H. Early development of an innovative building integrated wind, solar and rain water harvester for urban high rise application. Energy Build 2011.
[22] Pasquay T. Natural ventilation in high-rise buildings with double facades, saving or waste of energy. Energy Build 2004;36:381–9.
[23] Rosenfeld AH, Akbari H, Romm JJ, Pomerantz M. Cool communities: strategies for heat island mitigation and smog reduction. Energy Build 1998;28:51–62.
[24] Tuller SE. Onshore flow in an urban area: microclimatic effects. Int J Climatol 1995;15:1387–98.
[25] Kaldellis JK, Zafirakis D. The wind energy (r) evolution: a short review of a long history. Renew Energy 2011;36:1887–901.
[26] Kaldellis J, Zafirakis D, Kondili E, Papapostolou C. Trends, prospects and R&D directions of the global wind energy sector. available at http://proceedings.ewea.org/annual2012/allfiles2/1287_EWEA2012presentation.pdf.
[27] Leung DY, Yang Y. Wind energy development and its environmental impact: a review. Renew Sustain Energy Rev 2012;16:1031–9.

[28] Hoogwijk M, de Vries B, Turkenburg W. Assessment of the global and regional geographical, technical and economic potential of onshore wind energy. Energy Econ 2004;26:889–919.
[29] Sfetsos A. A comparison of various forecasting techniques applied to mean hourly wind speed time series. Renew Energy 2000;21:23–35.
[30] Seguro J, Lambert T. Modern estimation of the parameters of the Weibull wind speed distribution for wind energy analysis. J Wind Eng Ind Aerodyn 2000;85:75–84.
[31] Karki R, Billinton R. Cost-effective wind energy utilization for reliable power supply. IEEE Trans Energy Convers 2004;19:435–40.
[32] Lew DJ. Alternatives to coal and candles: wind power in China. Energy Policy 2000;28:271–86.
[33] Wilson R. Wind-turbine aerodynamics. J Wind Eng Ind Aerodyn 1980;5:357–72.
[34] Landsberg H, Maisel T. Micrometeorological observations in an area of urban growth. Bound-Layer Meteorol 1972;2:365–70.
[35] Nemitz E, Hargreaves KJ, McDonald AG, Dorsey JR, Fowler D. Micrometeorological measurements of the urban heat budget and CO2 emissions on a city scale. Environ Sci Technol 2002;36:3139–46.
[36] Walton A, Cheng A, Yeung W. Large-eddy simulation of pollution dispersion in an urban street canyon—part I: comparison with field data. Atmos Environ 2002;36:3601–13.
[37] Walton A, Cheng A. Large-eddy simulation of pollution dispersion in an urban street canyon—part II: idealised canyon simulation. Atmos Environ 2002;36:3615–27.
[38] Al-Bahadly I. Building a wind turbine for rural home. Energy Sustain Dev 2009;13:159–65.
[39] Walker SL. Building mounted wind turbines and their suitability for the urban scale-a review of methods of estimating urban wind resource. Energy Build 2011.
[40] Ricciardelli F, Polimeno S. Some characteristics of the wind flow in the lower urban boundary layer. J Wind Eng Ind Aerodyn 2006;94:815–32.
[41] Murakami S, Mochida A. 3-D numerical simulation of airflow around a cubic model by means of the k–ϵ model. J Wind Eng Ind Aerodyn 1988;31:283–303.
[42] Ledo L, Kosasih P, Cooper P. Roof mounting site analysis for micro-wind turbines. Renew Energy 2011;36:1379–91.
[43] Gasser RPH, Ehrlich G. An introduction to chemisorption and catalysis by metals. Phys Today 1987;40:128.
[44] Laboratory LLN. Simulating how the wind blows. Available from: ⟨https://www.llnl.gov/str/October01/Lee.html⟩; November 15, 2001.
[45] Walker SL. Building mounted wind turbines and their suitability for the urban scale—a review of methods of estimating urban wind resource. Energy Build 2011;43:1852–62.
[46] Landberg L, Myllerup L, Rathmann O, Petersen EL, Jørgensen BH, Badger J, et al. Wind resource estimation—an overview. Wind Energy 2003;6:261–71.
[47] Schallenberg-Rodriguez J. A methodological review to estimate techno-economical wind energy production. Renew Sustain Energy Rev 2013;21:272–87.
[48] Pavageau M, Schatzmann M. Wind tunnel measurements of concentration fluctuations in an urban street canyon. Atmos Environ 1999;33:3961–71.
[49] Hunt K, Nason GP. Wind speed modelling and short-term prediction using wavelets. Wind Eng 2001;25:55–61.
[50] Mortensen NG, Landberg L, Troen I, Lundtang Petersen E. Wind atlas analysis and application program (WAsP); 1993.
[51] Joselin Herbert G, Iniyan S, Sreevalsan E, Rajapandian S. A review of wind energy technologies. Renew Sustain Energy Rev 2007;11:1117–45.
[52] Eskin N, Artar H, Tolun S. Wind energy potential of Gokçeada Island in Turkey. Renew Sustain Energy Rev 2008;12:839–51.
[53] Safari B, Gasore J. A statistical investigation of wind characteristics and wind energy potential based on the Weibull and Rayleigh models in Rwanda. Renew Energy 2010;35:2874–80.
[54] Prasad R, Bansal R, Sauturaga M. Some of the design and methodology considerations in wind resource assessment. IET Renew Power Gener 2009;3:53–64.
[55] Lo Brano V, Orioli A, Ciulla G, Culotta S. Quality of wind speed fitting distributions for the urban area of Palermo, Italy. Renew Energy 2011;36:1026–39.
[56] Gao Y, Yao R, Li B, Turkbeyler E, Luo Q, Short A. Field studies on the effect of built forms on urban wind environments. Renew Energy 46, 2012, 148–154.
[57] Mithraratne N. Roof-top wind turbines for microgeneration in urban houses in New Zealand. Energy Build 2009;41:1013–8.
[58] Stathopoulos T, Wu H, Bédard C. Wind environment around buildings: a knowledge-based approach. J Wind Eng Ind Aerodyn 1992;44:2377–88.
[59] Ng E, Yuan C, Chen L, Ren C, Fung JC. Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: a study in Hong Kong. Landsc Urban Plan 2011;101:59–74.
[60] Oke TR. Initial guidance to obtain representative meteorological observations at urban sites. World Meteorological Organization Geneva; 2004:81.
[61] Grimmond C, Salmond J, Oke TR, Offerle B, Lemonsu A. Flux and turbulence measurements at a densely built-up site in Marseille: heat, mass (water and carbon dioxide), and momentum. J Geophys Res: Atmos 2004;109:1984–2012.
[62] Wieringa J. New revision of Davenport roughness classification. In: Proceedings of 3EACWE. Eindhoven, The Netherlands; 2001. p. 285–92.
[63] Lettau H. Note on aerodynamic roughness-parameter estimation on the basis of roughness-element description. J Appl Meteorol 1969;8:828–32.
[64] Raupach MR. Drag and drag partition on rough surfaces. Bound-Layer Meteorol 1992;60:375–95.
[65] Macdonald R, Griffiths R, Hall D. An improved method for the estimation of surface roughness of obstacle arrays. Atmos Environ 1998;32:1857–64.
[66] Raupach M, Thom A, Edwards I. A wind-tunnel study of turbulent flow close to regularly arrayed rough surfaces. Bound-Layer Meteorol 1980;18:373–97.
[67] Raupach M, Antonia R, Rajagopalan S. Rough-wall turbulent boundary layers. Appl Mech Rev 1991;44:1–25.
[68] Janajreh I, Su L, Alan F. Wind energy assessment: Masdar City case study. Renew Energy 2013;52:8–15.
[69] Su L, Janajreh I Wind energy assessment: Masdar city case study. In: Proceedings of the IEEE 8th International Symposium on Mechatronics and its Applications (ISMA); 2012. p. 1–6.
[70] Kim J-J, Baik J-J. Effects of inflow turbulence intensity on flow and pollutant dispersion in an urban street canyon. J Wind Eng Ind Aerodyn 2003;91:309–29.
[71] Janssen W, Blocken B, van Hooff T. Pedestrian wind comfort around buildings: comparison of wind comfort criteria based on whole-flow field data for a complex case study. Build Environ 2012.
[72] Salizzoni P, Van Liefferinge R, Soulhac L, Mejean P, Perkins RJ. Influence of wall roughness on the dispersion of a passive scalar in a turbulent boundary layer. Atmos Environ 2009;43:734–48.
[73] Razak AA, Hagishima A, Ikegaya N, Tanimoto J. Analysis of airflow over building arrays for assessment of urban wind environment. Build Environ 2012.
[74] Ahmad K, Khare M, Chaudhry K. Wind tunnel simulation studies on dispersion at urban street canyons and intersections—a review. J Wind Eng Ind Aerodyn 2005;93:697–717.
[75] Georgakis C, Santamouris M. Experimental investigation of air flow and temperature distribution in deep urban canyons for natural ventilation purposes. Energy Build 2006;38:367–76.
[76] Brown MJ, Streit GE. Emergency responders "Rules-of-Thumb" for air toxics releases in urban environments. Los Alamos National Laboratory: Publication Number: LA-UR-98-4539,1998.
[77] Yim SH-L, Fung JC-H, Lau AK-H, Kot SC. Air ventilation impacts of the wall effect resulting from the alignment of high-rise buildings. Atmos Environ 2009;43:4982–94.
[78] Gordeeva LG, Freni A, Krieger TA, Restuccia G, Aristov YI. Composites lithium halides in silica gel pores: methanol sorption equilibrium. Microporous Mesoporous Mater 2008;112:254–61.
[79] Spronken-Smith RA, Oke TR, Lowry WP. Advection and the surface energy balance across an irrigated urban park. Int J Climatol 2000;20:1033–47.
[80] Wood CR, Pauscher L, Ward H, Kotthaus S, Barlow J, Gouvea M, et al. Wind observations above an urban river using a new lidar technique, scintillometry and anemometry. Sci Total Environ 2013;442:527–33.
[81] Chou CC-K, Lee C-T, Chen W-N, Chang S-Y, Chen T-K, Lin C-Y, et al. Lidar observations of the diurnal variations in the depth of urban mixing layer: a case study on the air quality deterioration in Taipei, Taiwan. Sci Total Environ 2007;374:156–66.
[82] Cho M-R. The politics of urban nature restoration: the case of Cheonggyecheon restoration in Seoul, Korea. Int Dev Plan Rev 2010;32:145–65.
[83] Ching J. Urban-scale variations of turbulence parameters and fluxes. Bound-Layer Meteorol 1985;33:335–61.
[84] Song S.-H., Kang S.-i., Hahm N.-k. Implementation and control of grid connected AC–DC–AC power converter for variable speed wind energy conversion system. In: Proceedings of the eighteenth annual IEEE applied power electronics conference and exposition, APEC'03; 2003. p. 154–58.
[85] Eliasson I, Offerle B, Grimmond C, Lindqvist S. Wind fields and turbulence statistics in an urban street canyon. Atmos Environ 2006;40:1–16.
[86] Dutton A, Halliday J, Blanch M. The feasibility of building-mounted/integrated wind turbines (BUWTs): achieving their potential for carbon emission reductions. Energy Research Unit, CCLRC; 2005.
[87] Li J, Wang W-S, Song J-H. Modeling and dynamic simulation of variable speed wind turbine. J Power Syst Technol 2003;9:005.
[88] Chen Z, Guerrero JM, Blaabjerg F. A review of the state of the art of power electronics for wind turbines. IEEE Trans Power Electron 2009;24:1859–75.
[89] Aho J, Buckspan A, Laks J, Fleming P, Jeong Y, Dunne F, et al. A tutorial of wind turbine control for supporting grid frequency through active power control. In: Proceedings of the IEEE American Control Conference (ACC); 2012. p. 3120–31.
[90] Eggers A, Holley W, Digumarthi R, Chaney K. Exploratory study of HAWT blade throw risk to nearby people and property. In: Proceedings of the ASME wind energy symposium. Reno, Nevada; January 8–11, 2001. p. 355–67.
[91] Paulides J, Encica L, Jansen J, Lomonova E, van Wijck D. Small-scale urban Venturi wind turbine: direct-drive generator. In: Proceedings of the IEEE international conference electric machines and drives, IEMDC'09; 2009. p. 1368–73.
[92] Cace J, ter Horst RE, Syngellakis HK, Power I. Urban wind turbines. Guidlines for small wind turbines in the built environment. Article online: www.urban-wind.org; 2007. p. 1–41.
[93] Cace J, et al. Urban wind turbines. Guidlines for small wind turbines in the built environment. Available from: ⟨www.urban-wind.org⟩; 2007.
[94] Sicot C, Devinant P, Loyer S, Hureau J. Rotation and turbulence effects on a HAWT blade airfoil aerodynamics. Wind Energy. Springer; 2007; 221–6.
[95] Eriksson S, Bernhoff H, Leijon M. Evaluation of different turbine concepts for wind power. Renew Sustain Energy Rev 2008;12:1419–34.

[96] Zhong Y, Critoph RE, Thorpe R, Tamainot-Telto Z, Aristov YI. Isothermal sorption characteristics of the BaCl⟨sub⟩2⟨/sub⟩–NH⟨sub⟩3⟨/sub⟩ pair in a vermiculite host matrix. Appl Therm Eng 2007;27:2455–62.
[97] Eun T-H, Song H-K, Hun Han J, Lee K-H, Kim J-N. Enhancement of heat and mass transfer in silica-expanded graphite composite blocks for adsorption heat pumps: part I. Characterization of the composite blocks. Int J Refrig 2000;23:64–73.
[98] Liu Y, Wang R. Pore structure of new composite adsorbent SiO2 · *x*-H2O · *y*CaCl2 with high uptake of water from air. Sci China Ser E: Technol Sci 2003;46:551–9.
[99] Trade H. Wes Tulipo turbine-wind energy solution. Available from: ⟨http://www.hellotrade.com/wind-energy-solution/wes-tulipo-turbine.html⟩.
[100] UK HE. Wind power. Available from: ⟨http://www.homeenergyuk.com/domestic/green-power/wind-power⟩.
[101] Alibaba. WindWall 3 kW windturbine. Available from: ⟨http://french.alibaba.com/product-free/windwall-3 kw-windturbine-109199832.html⟩.
[102] Wikipedia tfe. Mesoporous silicate. Available from: ⟨http://en.wikipedia.org/wiki/Mesoporous_silicate⟩.
[103] Peacock A, Jenkins D, Ahadzi M, Berry A, Turan S. Micro wind turbines in the UK domestic sector. Energy Build 2008;40:1324–33.
[104] Goldberg SB. Vertical-axis wind turbine with a twisted blade configuration. Google patents; 1995.
[105] Ferrigno KJ. Challenges and strategies for increasing adoption of small wind turbines in urban areas. Massachusetts Institute of Technology; 2010.
[106] Paraschivoiu I. Double-multiple streamtube model for studying vertical-axis wind turbines. J Propuls Power 1988;4:370–7.
[107] Lambie B. Aeroelastic investigation of a wind turbine airfoil with self-adaptive camber; 2011.
[108] McGowan R, Lozano R, Raghav V, Komerath N. Vertical Axis Micro Wind Turbine Design for Low Tip Speed Ratios. Georgia Institute of Technology, Atlanta, United States, Conference name: Proceedings of the 3 rd International Multi-Conference on Complexity, Informatics and Cybernetics, Orlando, FL, 2012.
[109] Kirsch J. Design of a small wind turbine for electric power generation (1–5 kW); 2009.
[110] Benedict M, Jarugumilli T, Chopra I. Experimental optimization of MAV-scale cycloidal rotor performance. J Am Helicopter Soc 2011;56:22005-1–22005-11.
[111] Magazine G. Home wind power, the Turby. Available from: ⟨http://greenermagazine.blogspot.com/2006/03/home-wind-power-turby.html⟩ [accessed 09.03.06].
[112] Trialcom. Windside (replica). Available from: ⟨http://www.trialcom.it/windside.html⟩.
[113] Spol I. Easy vertical-Ropatec turbine. Available from: ⟨http://www.impel.cz/vetrne_elektrarny/index.php?sekce=7&podsekce=31&lang=en⟩.
[114] Dose W Wind turbine types-Gorlov helical turbine. 2008.
[115] Knight J. Urban wind power: breezing into town. Nature 2004;430:12–3.
[116] Greenblatt D, Schulman M, Ben-Harav A. Vertical axis wind turbine performance enhancement using plasma actuators. Renew Energy 2012;37:345–54.
[117] Ashok S. Optimized model for community-based hybrid energy system. Renewable energy 2007;32:1155–64.
[118] Mathew S. Wind energy: fundamentals, resource analysis and economics; 2006.
[119] Kaundinya DP, Balachandra P, Ravindranath N. Grid-connected versus stand-alone energy systems for decentralized power—a review of literature. Renew Sustain Energy Rev 2009;13:2041–50.
[120] Bowen A, Lindley D. A wind-tunnel investigation of the wind speed and turbulence characteristics close to the ground over various escarpment shapes. Bound-Layer Meteorol 1977;12:259–71.
[121] Soderlund L, Eriksson J-T, Salonen J, Vihriala H, Perala R. A permanent-magnet generator for wind power applications. IEEE Trans Magn 1996;32:2389–92.
[122] Khan M, Iqbal M. Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland. Renew Energy 2005;30:835–854.
[123] Bindner H, Rosas PA, Teodorescu R, Blaabjerg F. Stand-alone version of the 11 kW Gaia wind turbine. Riso; 2004.
[124] ⟨http://www.soulofamerica.com/cleveland-family-attractions.phtml⟩.
[125] Abohela I, Hamza N, Dudek S, Urban Wind Turbines. Integration in the built form and environment. UK: School of Architecture, Planning and Landscape, Newcastle University; 2010.
[126] Chong W, Fazlizan A, Poh S, Pan K, Ping H. Early development of an innovative building integrated wind, solar and rain water harvester for urban high rise application. Energy Build 2012;47:201–7.
[127] Chong W, Fazlizan A, Poh S, Pan K, Hew W, Hsiao F. The design, simulation and testing of an urban vertical axis wind turbine with the omni-direction-guide-vane. Appl Energy 2013.
[128] Sharpe T, Proven G. Crossflex: concept and early development of a true building integrated wind turbine. Energy Build 2010;42:2365–75.
[129] Ardente F, Beccali M, Cellura M, Mistretta M. Energy and environmental benefits in public buildings as a result of retrofit actions. Renew Sustain Energy Rev 2011;15:460–70.
[130] Bannon TA. FAR Part 139 certificated airports shifting towards environmentally-friendly practices; 2012.
[131] Solutions GE. Architectural wind turbines case study. Available from: ⟨http://www.groomenergy.com/case_study_wind.html⟩.
[132] Today U. Airports go for green with eco-friendly efforts. Available from: ⟨http://usatoday30.usatoday.com/travel/flights/2008-09-16-green-airports_N.htm⟩ [accessed 17.09.08].
[133] McDermott M. 10 small-scale wind turbines cut NYC apartment building's electric costs in half. Available from: ⟨http://www.treehugger.com/renewable-energy/10-small-scale-wind-turbines-cut-nyc-apartment-buildingatms-electric-costs-in-half.html⟩.
[134] Ayhan D, Sağlam Ş. A technical review of building-mounted wind power systems and a sample simulation model. Renew Sustain Energy Rev 2012;16:1040–9.
[135] Chong W, Naghavi M, Poh S, Mahlia T, Pan K. Techno-economic analysis of a wind-solar hybrid renewable energy system with rainwater collection feature for urban high-rise application. Appl Energy 2011.
[136] Minner K. COR/Oppenheim Architecture+Design. Available from: ⟨http://www.archdaily.com/tag/oppenheim-architecture-design/⟩; 2011.
[137] Al-Kodmany K. Eco-iconic skyscrapers: review of new design approaches. Int J Sustain Des 2010;1:314–34.
[138] Smith RF, Killa S. Bahrain World Trade Center (BWTC): the first large-scale integration of wind turbines in a building. Struct Des Tall Spec Build 2007;16:429–39.
[139] Laumer J. “Twin Towers” Bahrain World Trade Center with three wind turbines. Available from; ⟨http://www.treehugger.com/renewable-energy/twin-towers-bahrain-world-trade-center-with-three-wind-turbines.html⟩ [accessed 10.04.08].
[140] Beller C. Urban wind energy-state of the art 2009. Danmarks Tekniske Universitet, Risø Nationallaboratoriet for Bæredygtig Energi; 2009.
[141] Aristov YI, Tokarev M, Cacciola G, Restuccia G. Selective water sorbents for multiple applications, 1. CaCl2 confined in mesopores of silica gel: sorption properties. React Kinet Catal Lett 1996;59:325–33.
[142] Cangelli E, Fais L. Energy and environmental performance of tall buildings: state of the art. Adv Build Energy Res 2012;6:36–60.
[143] COR Project-Oppenheim Archtecture+Design. Available from: ⟨http://www.oppenoffice.com/index2.htm⟩; 2011.
[144] Urbika. Image Pearl River Tower Guangzhou. Available from: ⟨http://www.urbika.com/images/view/5960⟩; 2013.
[145] Moorhouse A, Elliott A, Eastwick G, Von Hunerbein S, Waddington D. Noise and vibration from building-mounted micro wind turbines Part 1: review and proposed methodology; 2011.
[146] Moorhouse A, Elliott A, Eastwick G, Evans T, Ryan A, Von Hunerbein S, et al. Noise and vibration from building-mounted micro wind turbines Part 2: results of measurements and analysis; 2011.
[147] Gordeeva L, Restuccia G, Cacciola G, Aristov YI. Selective water sorbents for multiple applications, 5. LiBr confined in mesopores of silica gel: sorption properties. React Kinet Catal Lett 1998;63:81–8.
[148] Sun X, Huang D, Wu G. The current state of offshore wind energy technology development. Energy 2012.
[149] Jones CR, Eiser JR. Identifying predictors of attitudes towards local onshore wind development with reference to an English case study. Energy Policy 2009;37:4604–14.
[150] Han J, Mol AP, Lu Y, Zhang L. Onshore wind power development in China: challenges behind a successful story. Energy Policy 2009;37:2941–51.
[151] Bilgili M, Yasar A, Simsek E. Offshore wind power development in Europe and its comparison with onshore counterpart. Renew Sustain Energy Rev 2011;15:905–15.
[152] Zhixin W, Chuanwen J, Qian A, Chengmin W. The key technology of offshore wind farm and its new development in China. Renew Sustain Energy Rev 2009;13:216–22.
[153] Esteban MD, Diez JJ, López JS, Negro V. Why offshore wind energy? Renew Energy 2011;36:444–50.
[154] Da Z, Xiliang Z, Jiankun H, Qimin C. Offshore wind energy development in China: current status and future perspective. Renew Sustain Energy Rev 2011;15:4673–84.
[155] Wilkes J, Moccia J, Arapogianni A, Dragan M, Plytas N, Genachte A, et al. The European offshore wind industry key 2011 trends and statistics. The European Wind Energy Association (EWEA). 2012.
[156] Association EWE. The European offshore wind industry key 2011 trends and statistics; 2012, Article available at http://www.ewea.org/fileadmin/ewea_-documents/documents/publications/statistics/EWEA_stats_offshore_2011_0.
[157] Arapogianni A, Dragan M, Wilkes J, Moccia J, Guillet J. The European offshore wind industry—key trends and statistics: 1st half 2011. European Wind Energy Association; 2011.
[158] Edwards I, Dalry CD. Overcoming challenges for the offshore wind industry and learning from the oil and gas industry. Power cluster report No. 12345:R001A; 2011.
[159] Khan N, Su Y, Riffat SB. A review on wind driven ventilation techniques. Energy Build 2008;40:1586–604.
[160] Olsen EL, Chen QY. Energy consumption and comfort analysis for different low-energy cooling systems in a mild climate. Energy Build 2003;35:560–71.
[161] Mochida A, Yoshino H, Takeda T, Kakegawa T, Miyauchi S. Methods for controlling airflow in and around a building under cross-ventilation to improve indoor thermal comfort. J Wind Eng Ind Aerodyn 2005;93:437–49.
[162] Lien J, Ahmed N.Wind driven ventilation for enhanced indoor air quality; 2011.
[163] Lai CM. Prototype development of the rooftop turbine ventilator powered by hybrid wind and photovoltaic energy. Energy Build 2006;38:174–80.
[164] Construction Magazine Network. Available from: ⟨http://www.constructionmagnet.com/green-building/product_profile_solar_2011⟩.

[165] Shun S, Ahmed NA. Utilizing wind and solar energy as power sources for a hybrid building ventilation device. Renew Energy 2008;33: 1392–7.
[166] Mochida A, Lun IYF. Prediction of wind environment and thermal comfort at pedestrian level in urban area. J Wind Eng Ind Aerodyn 2008;96:1498–527.
[167] Memon RA, Leung DYC, Liu CH. Effects of building aspect ratio and wind speed on air temperatures in urban-like street canyons. Build Environ 2010;45:176–88.
[168] Hang J, Li Y, Sandberg M, Claesson L. Wind conditions and ventilation in high-rise long street models. Build Environ 2010;45:1353–65.
[169] Sun L, Nottrott A, Kleissl J. Effect of hilly urban morphology on dispersion in the urban boundary layer. Build Environ 2012;48:195–205.
[170] Belâev LS. World energy and transition to sustainable development. Kluwer Academic Publishers; 2002.
[171] Krohn S, Morthorst PE, Awerbuch S. The economics of wind energy. European Wind Energy Association 2009:28–9.
[172] Booker J, Mellor P, Wrobel R, Drury D. A compact, high efficiency contra-rotating generator suitable for wind turbines in the urban environment. Renew Energy 2010;35:2027–33.
[173] Mertens S. Wind Energy in the Built Environment-concentrator effects of buildings. Wind Eng 2006;30:451–2.
[174] Campbell D, Stankovic S, Graham M, Parkin P, van Duijvendijk M, de Gruiter T, et al. Wind energy for the built environment (Project Web). London: Imperial College, Mecal Applied Mechanice and the University of Stuttgart; 2001.
[175] Jobert A, Laborgne P, Mimler S. Local acceptance of wind energy: factors of success identified in French and German case studies. Energy Policy 2007;35:2751–60.
[176] Horbaty R, Huber S, Ellis G. Large-scale wind deployment, social acceptance. Wiley Interdiscip Rev: Energy Environ 2012;1:194–205.